

# Mitigation of HVAC-induced low-frequency noise at the Virgo detector during O4 preparation

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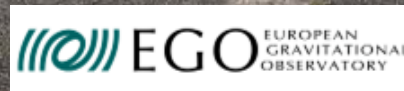
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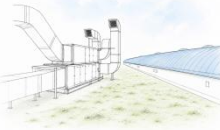
14<sup>th</sup> KAGRA International Workshop

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# Outline



- \* Motivation and HVAC system overview
- \* Noise investigation campaign
- \* Key mitigation actions and results
- \* Applying the lessons to Virgo O5
- \* Implications for future detectors

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## Classical and Quantum Gravity

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### Reducing the Virgo site infrastructure noise in preparation of the O4 observing run

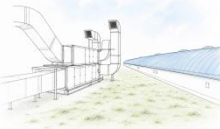
Irene Fiori, Federico Paoletti, Roberto Passaquieti, Maria Concetta Tringali, Lorenzo Pierini, Francesca Bucci, Massimo Lenti and Alessandro Longo

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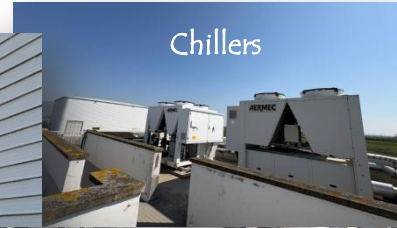
DOI 10.1088/1361-6382/ae68d2

# Motivation



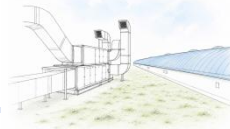
- \* The heating ventilation air conditioning systems (HVAC) generate acoustic, seismic and electromagnetic noise at *low frequency* (below 100 Hz).
- \* The Virgo detector is equipped with a total of nine HVAC systems that serve clean areas of varying volumes and cleanliness requirements.

System	Serving area	Volume (m <sup>3</sup> )	AHU location
CEB AHU	Experimental hall of the Central building	8370	Inside the Central building
CEB Clean rooms	Clean rooms in the Central building	507	Inside the Central building
INJ AHU	Laser Laboratory SAS. Atrium	507 (ISO 7)	Outdoor
DET AHU	Detection laboratory. SAS	468 (ISO 7)	Outdoor
NEB AHU	Experimental hall of the North end building	4995	Outdoor (Technical area)
WEB AHU	Experimental hall of the West end building	4995	Outdoor (Technical area)
MCB AHU	Experimental hall of the Mode cleaner building	782	Outdoor
FCIM and FCEM AHUs	Input and End clean area of the Filter cavity	57 (ISO 7)	Outdoor



- \* In preparation for O4 run, a comprehensive investigation was carried out to identify the most critical noise sources within this infrastructure and to trace their transmission paths into the experimental areas.

# HVAC system overview



\* The HVAC system is a complex system because of the extension of the apparatus and the difficulty in identifying the main culprits among the multiplicity of noise paths towards the experimental areas.

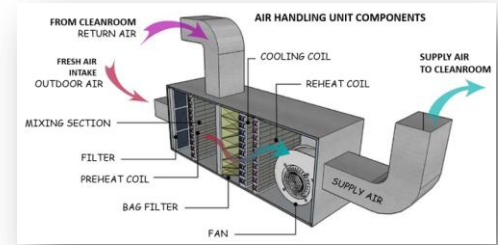
\* The HVAC system components:

✓ **air handling unit (AHU)**

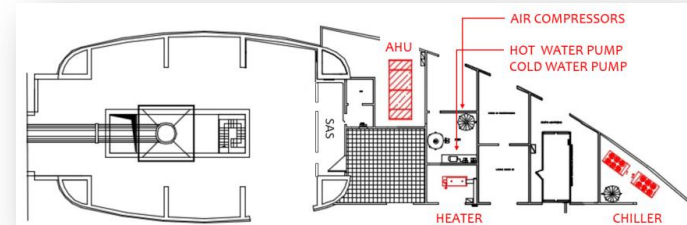
- air circulator (fan)\*
- electrical motor (driven by inverter)
- air distribution (ducts)
- multi-compartment stainless-steel enclosure housing fan and motor

✓ **cold and hot water production** (chillers and heaters);

✓ **water distribution system** (pumps and pipes).



North End Building (NEB)

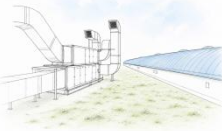


\* Belt-driven or direct-drive fan-motor configurations.

\* Fan speed controlled via variable frequency drives (*inverter*) to optimize airflow.

# HVAC noise signature

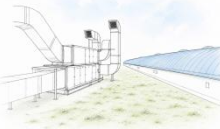
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## What are we looking for?

- \* The low-frequency noise (acoustic, seismic and EM) of HVAC plants is characterized by:
  - \* **broadband colored noise** arises from turbulent airflow within the ducts and fan enclosure which can excite resonance of the mechanical components and acoustic mode of the rooms;
  - \* **spectral lines** are typically associated with rotating machinery (rotation frequency + harmonics) and power electronics (e.g. inverter frequencies).
  - \* **intermittent noise** due to the operational cycle of devices such as chillers or boilers.

# Investigating HVAC noise



\* A dedicated investigation campaign was carried out to identify dominant noise sources and coupling paths.

✓ **Selective switch-off test**

of the devices to identify noise contributions and spectral components

✓ **Air ducts disconnection test**

to discriminate between airborne noise in ducts and other paths

✓ **Controlled slowdown of the AHU**

to evaluate the dependence of acoustic noise on fan speed

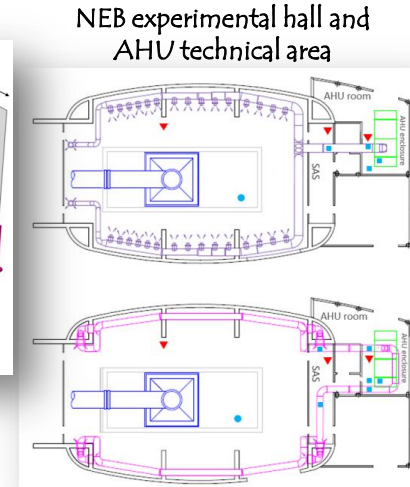
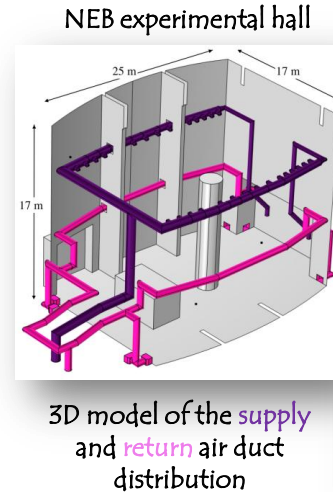
✓ **Magnetic noise characterization**

measurement campaign to characterize the magnetic noise generated by the AHU system

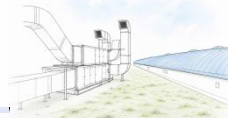
\* **Application of mitigation solutions**

\* **Test setup**

- North end building (NEB) HVAC was the test-bench of this noise studies
- Temporary sensors installed near HVAC devices and along suspected noise transmission paths



# Noise investigation: air ducts disconnection



\* Low frequency acoustic noise generated by the AHU can follow different paths to the experimental hall:

- **through walls**  
airborne transmission through separating walls
- **through vibrating ducts**  
ducts act as acoustic transducer
- **through airborne noise in ducts**  
fan/turbulent airflow propagation
- **at the outlets**



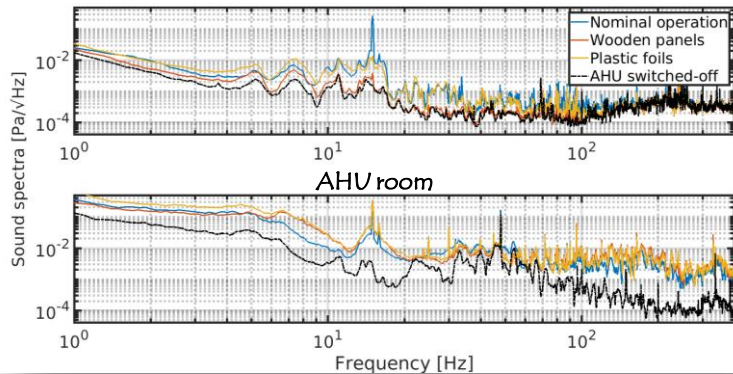
Plastic foil



Wooden board



Experimental hall

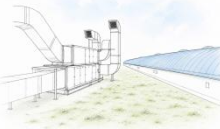


\* Temporary disconnection of supply and return ducts from the AHU enclosure.

\* Duct openings alternatively sealed with **plastic foil** and **rigid wooden board**.

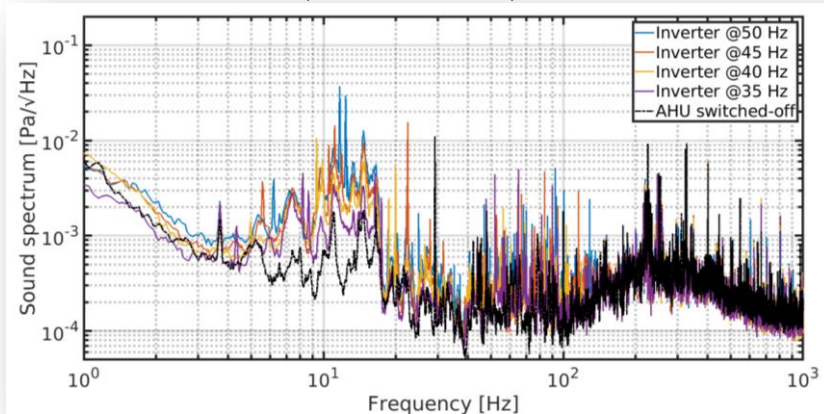
\* Only wooden board blocked the airborne sound propagation  
→ airborne noise transmitted through the ducts is the dominant path from the AHU to the hall.

# Noise investigation: fan slowdown



\*Fan speed strongly affects acoustic noise generation and higher rotational speeds increase turbulent airflow, leading to broadband low-frequency noise.

Acoustic spectrum of the NEB experimental hall



\*A controlled reduction of the AHU fan speed was performed by means of inverter to assess the dependence of acoustic noise on operating conditions.

\*Reduced fan speeds led to substantial broadband noise reduction.

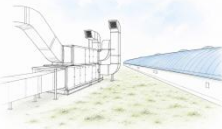
## Constrains

- \* Further speed reduction must remain compatible with
  - temperature, humidity, overpressure/cleanliness requirements;
  - prevention of motor overheating;
  - outdoor temperature conditions during the hot season.

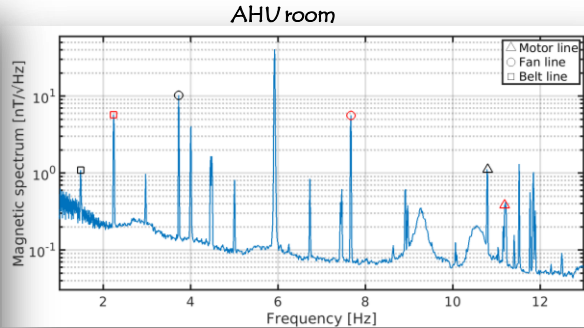
Measured parameter values during the slowdown test of NEB AHU

Inverter frequency (Hz)	Motor frequency (Hz)		Fan frequency (Hz)		Belt frequency (Hz)	
	Theory	Measured	Theory	Measured	Theory	Measured
50 (nominal)	24.25	24.95	11.45	11.70	6.20	6.18
45	21.82	22.27	11.30	10.53	5.58	5.56
40	19.40	19.96	9.16	9.36	4.96	4.95
35	16.97	17.47	8.00	8.19	4.34	4.33

# Noise investigation: magnetic noise



\*Magnetic measurements showed that HVAC systems generate electromagnetic disturbances.



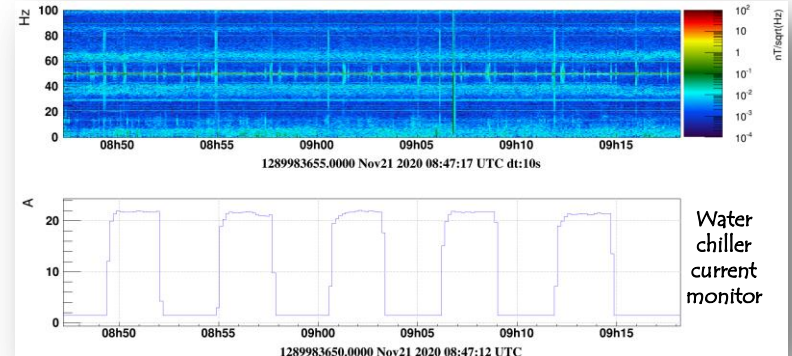
\* Magnetic spectral lines associated with the AHU fan, motor, and belts were identified in ambient magnetic spectra

→ vibrations of large metallic structures (e.g. the AHU enclosure) modulate the ambient magnetic field.

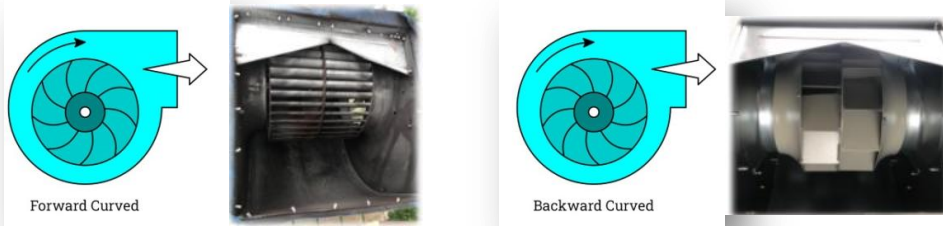
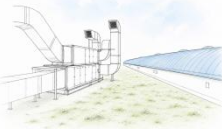
\*Magnetic glitches are typically generated during the start-up of heavy, periodically switching loads, such as chillers (~20-80 Hz) and air compressors (~40-60 Hz) in the HVAC systems

→ periodic voltage/current ripples in the mains can inject disturbance currents into the experimental electrical grid, whose cables radiate the associated magnetic fields.

Magnetic spectrogram (NEB experimental hall)

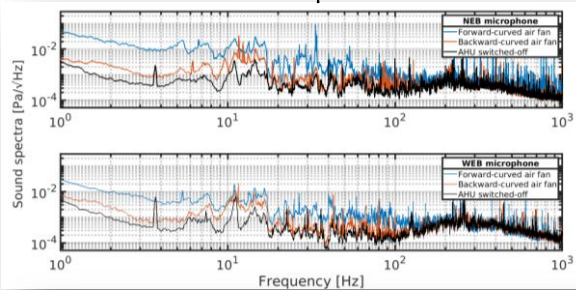


# Acoustic noise mitigation

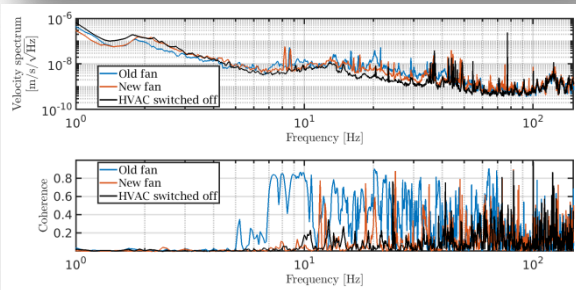


- \* Fan design strongly impacts low-frequency acoustic emissions.
- \* The original forward-curved fan was replaced with a *backward-curved* model with comparable operational specifications.

NEB and WEB experimental halls

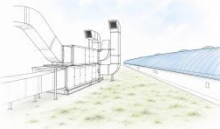


- \* Broadband acoustic noise was substantially reduced, starting from a few hertz and up to 100 Hz.



- \* A concurrent reduction of hall floor seismic vibration was also measured in the frequency range  $\sim(7-70)$  Hz
  - airborne acoustic noise may excite the lightweight scaffolding around the vacuum chamber, coupling to floor vibrations.
- \* The same fan replacement was implemented for WEB AHU system, yielding similar results.

# Seismic noise mitigations (1/2)



- \*The HVAC water distribution system was another relevant seismic noise path.
- \*Vibration noise can propagate either through floors and walls as *structure-borne* noise, or as pressure fluctuations within the fluid as *water-borne* noise.

Damping supports

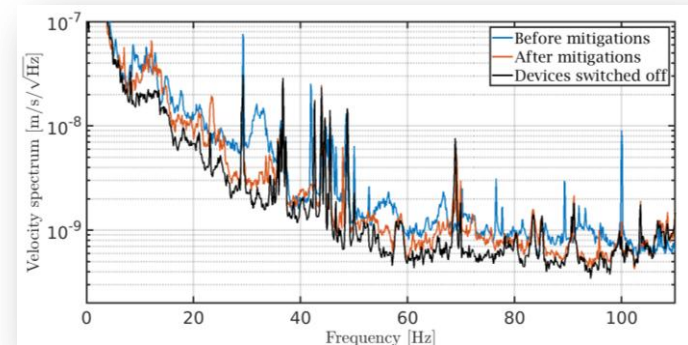
Through-holes in the wall



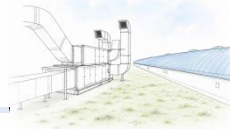
## Mitigation actions:

- damped spring isolation of pumps and boilers;
- flexible decoupling of pump–pipe connections (rubber joints);
- structural decoupling of pipes from walls using spring;
- reduction of rigid wall mechanical coupling.

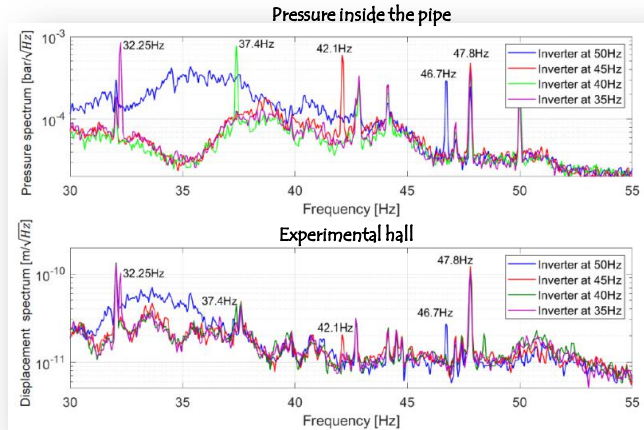
- \*The implemented mitigation actions significantly reduced the seismic noise level (red curve) of the experimental hall floor in the frequency range  $\sim(15-100)$  Hz.



# Seismic noise mitigations (2/2)



- \* Pressure fluctuations generated by the water circulation pumps can propagate through the pipe network and excite structural vibrations.

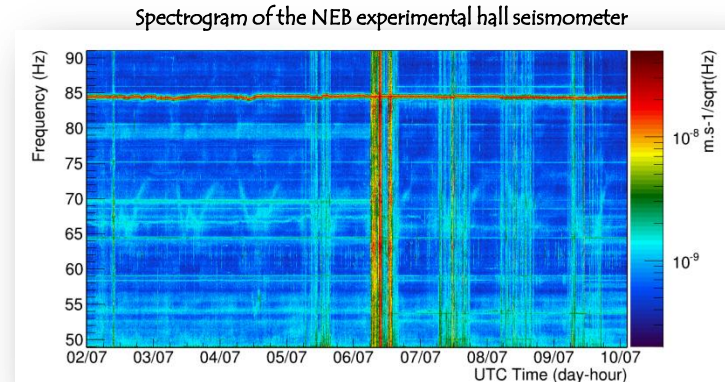


- \* A controlled pump slowdown reduced both pressure fluctuations and the corresponding hall seismic noise.

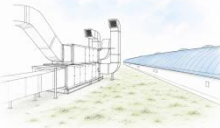
- \* When the pump operated at 45 Hz, a clear reduction of seismic noise was observed in the experimental hall in the 30–40 Hz range.

- \* Residual water in pipes connected to inactive clean-room AHUs transmitted chiller-induced vibrations to the hall structure.

- \* Closing the upstream valve reduced both pipe vibration and floor seismic noise  $\sim$ (65–80) Hz.



# Good mitigation practices



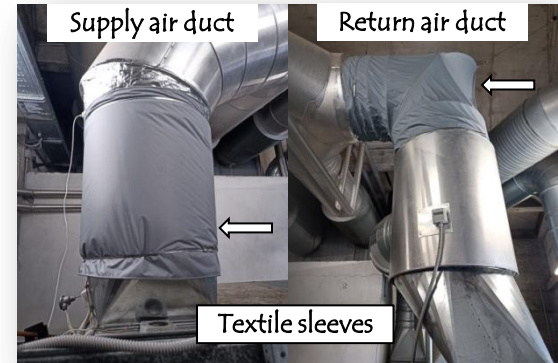
\* Although not always producing measurable hall-level reductions, these remain important good practices for low-noise infrastructures.

\* Disconnection of the supply and return air ducts from AHU enclosure by means of textile sleeves.

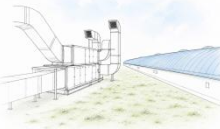
\* Insertion of the dumping supports under AHU enclosure and fan-motor case.

\* Damping panel installation on AHU enclosure, SAS air ducts and on part of the supply air duct in the experimental hall.

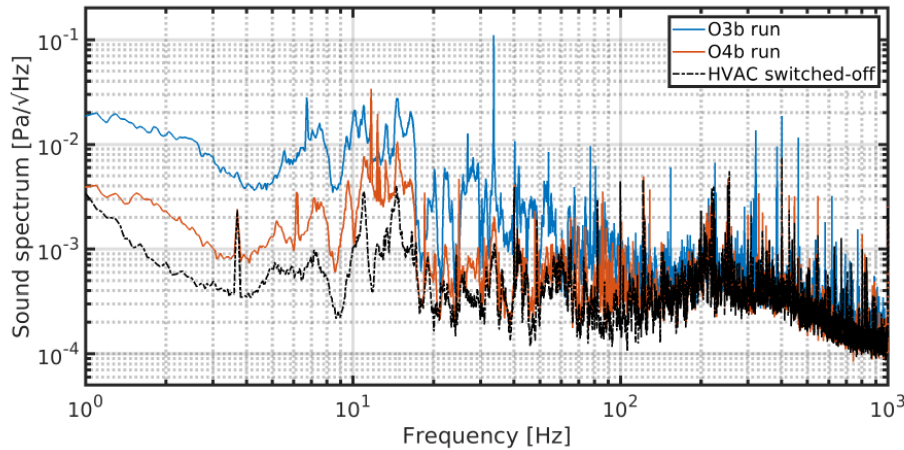
\* Internal damping treatment of the fan compartment



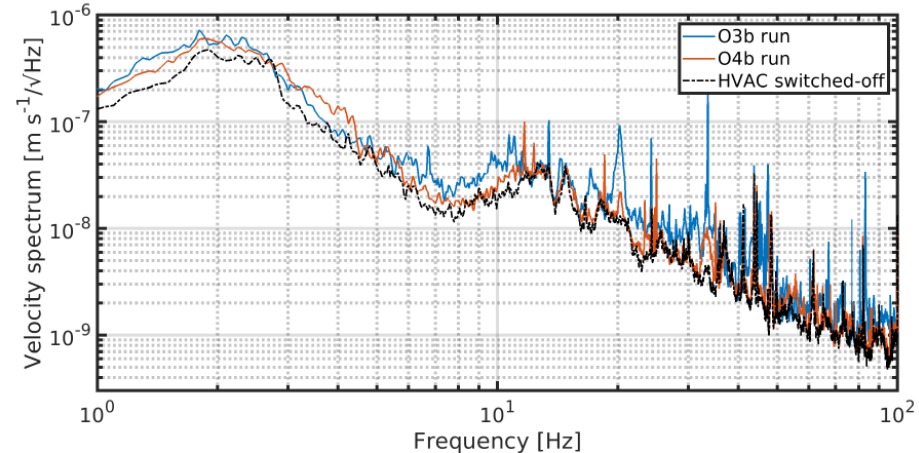
# Overall environmental improvement



Acoustic spectrum of the NEB experimental hall

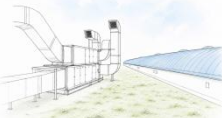


Seismic spectrum of the NEB experimental hall



Significant reduction of both acoustic and seismic environmental noise in the experimental hall.

# Toward quieter clean-room infrastructure for O5



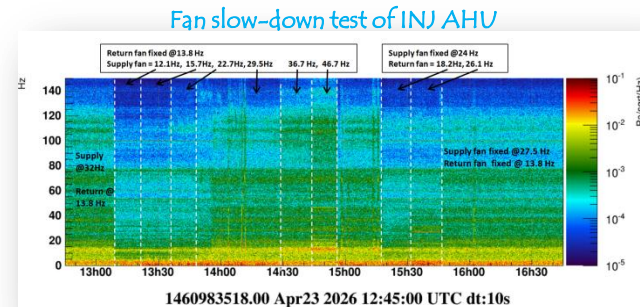
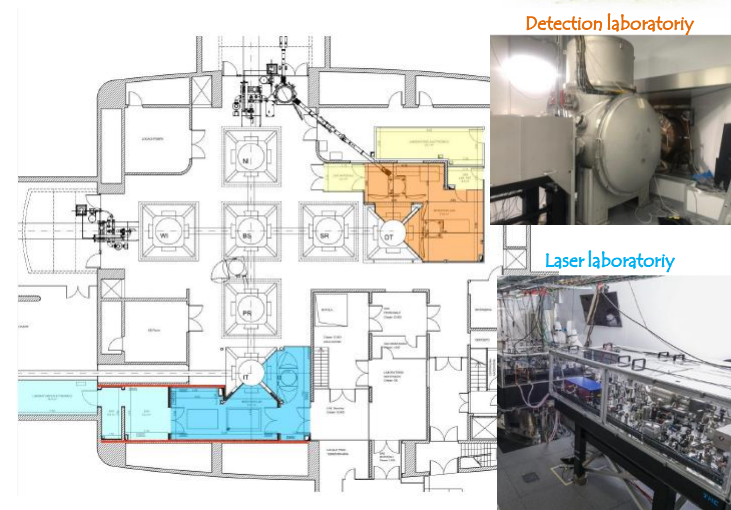
\* The lessons learned from the O4 mitigation campaign are now being applied to the design of the new INJ and DET clean-room infrastructure for O5.

- In the *stable-cavity configuration*, the INJ and DET clean-room volumes will increase by approximately 30% ([VIR-0909A-25](#)).

\* Current studies focus on reducing the HVAC acoustic noise inside the laboratories by (elog # [67829](#) ,#[67876](#),# [68181](#)):

- controlled fan slowdown tests;
- long-term monitoring of environmental parameters (temperature, humidity, overpressure/cleanliness);
- optimization of airflow distribution settings (valve's opening).

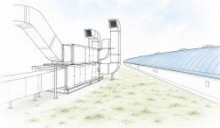
\* The goal is to identify a low-noise operating configuration compatible with environmental stability requirements.



Acoustic spectrogram

# Conclusions

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- \* HVAC infrastructure can represent a significant source of low-frequency acoustic, seismic, and electromagnetic noise in gravitational-wave detectors.
- \* A systematic investigation campaign allowed the identification of dominant coupling paths and the implementation of targeted mitigation actions.
- \* Virgo infrastructure was designed more than 25 years ago, when low-noise requirements for technical systems were not yet a primary design driver.
- \* The experience gained at Virgo will provide valuable lessons and practical guidelines for the design of low-noise HVAC and technical infrastructure in future detectors such as ET.



Thank you for your attention!